

Probing magnetism at the nano-scale: novel physics and emerging technologies

Eric Fullerton

San Jose Research Center

Hitachi Global Storage Technologies

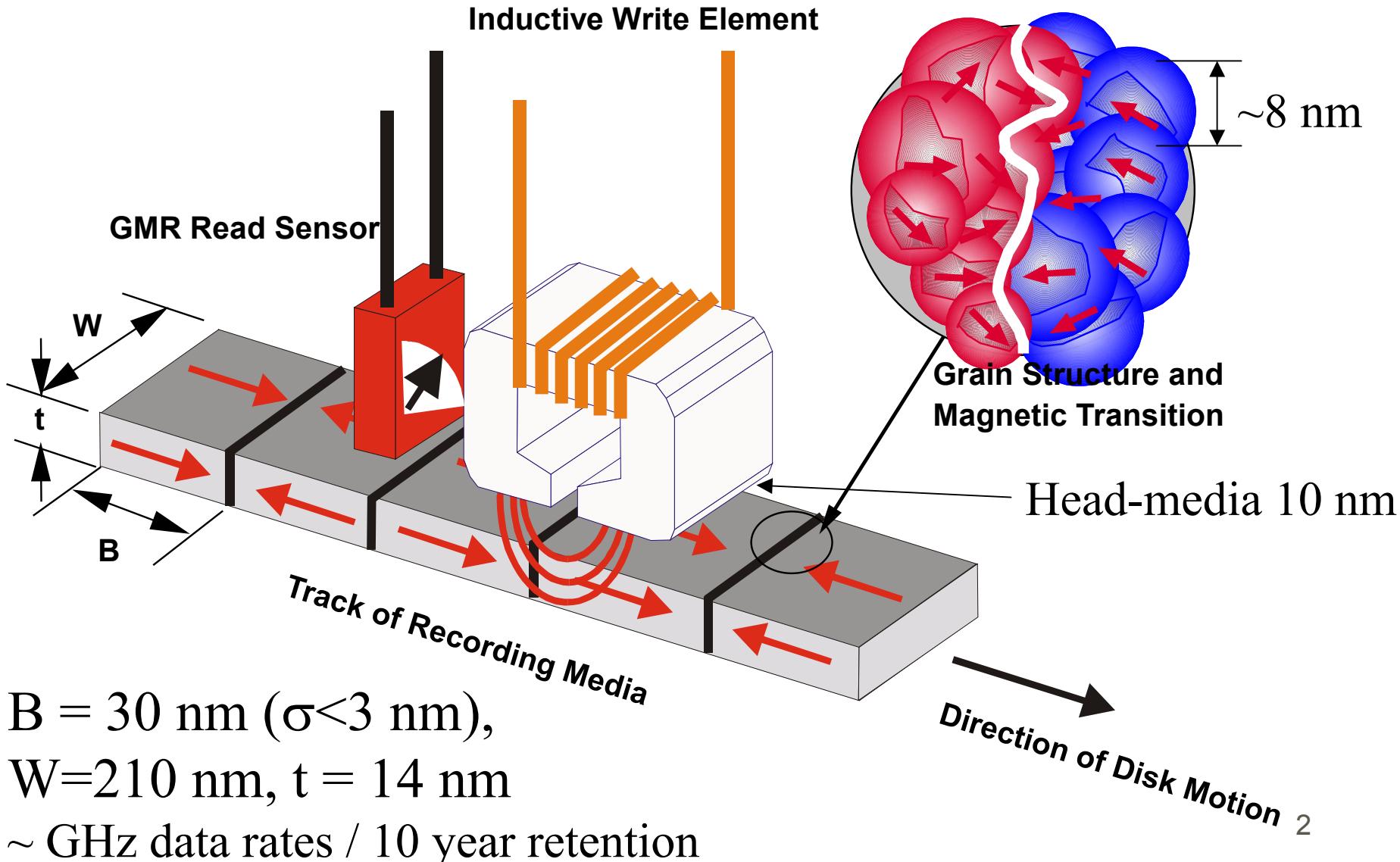
Functional magnetic materials and nano ‘issues’

Opportunities for resonant x-ray scattering

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Inspire the Next[®]

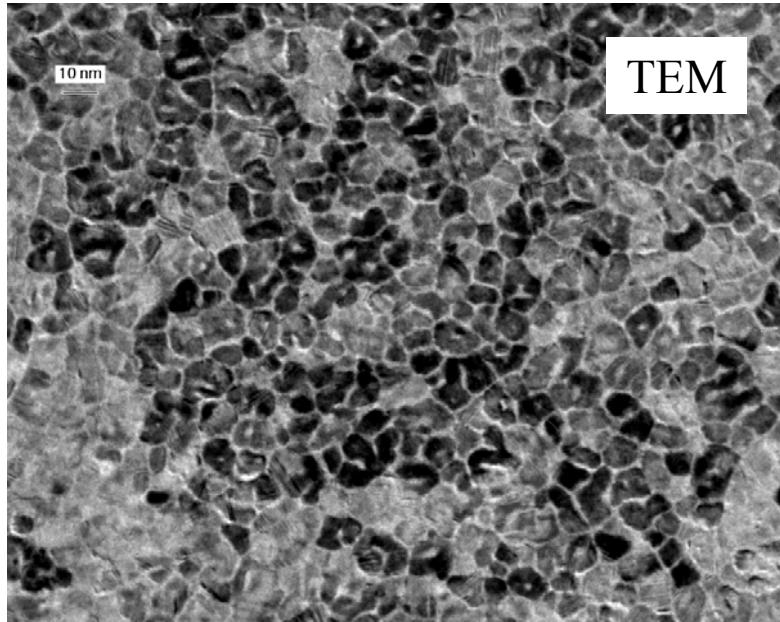


Magnetic recording components



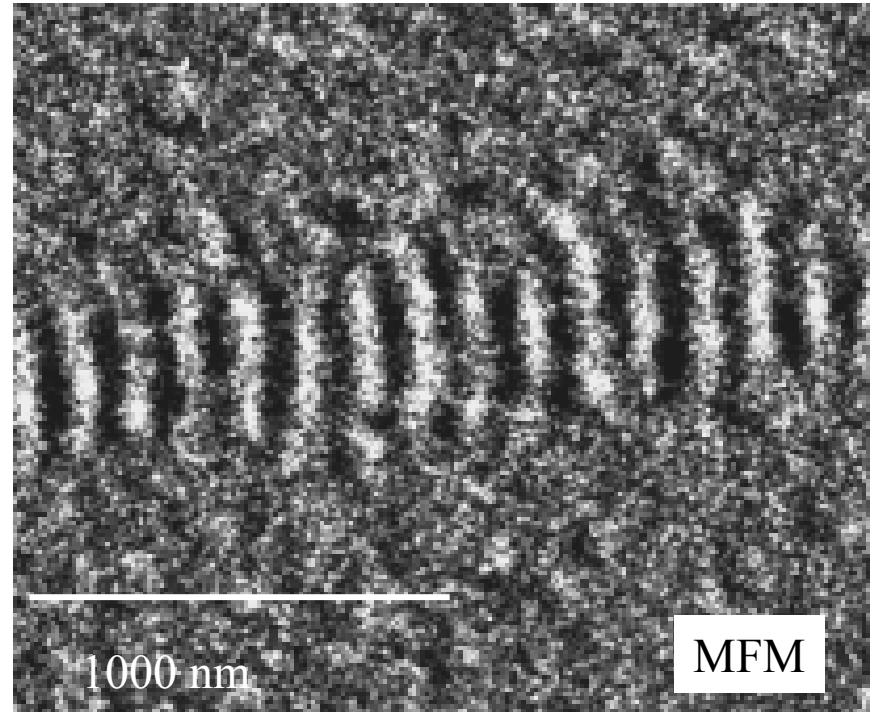
Media: TEM and MFM images

CoPtCrB alloy



100 nm

$\langle D \rangle = 8.5 \text{ nm}$



1000 nm

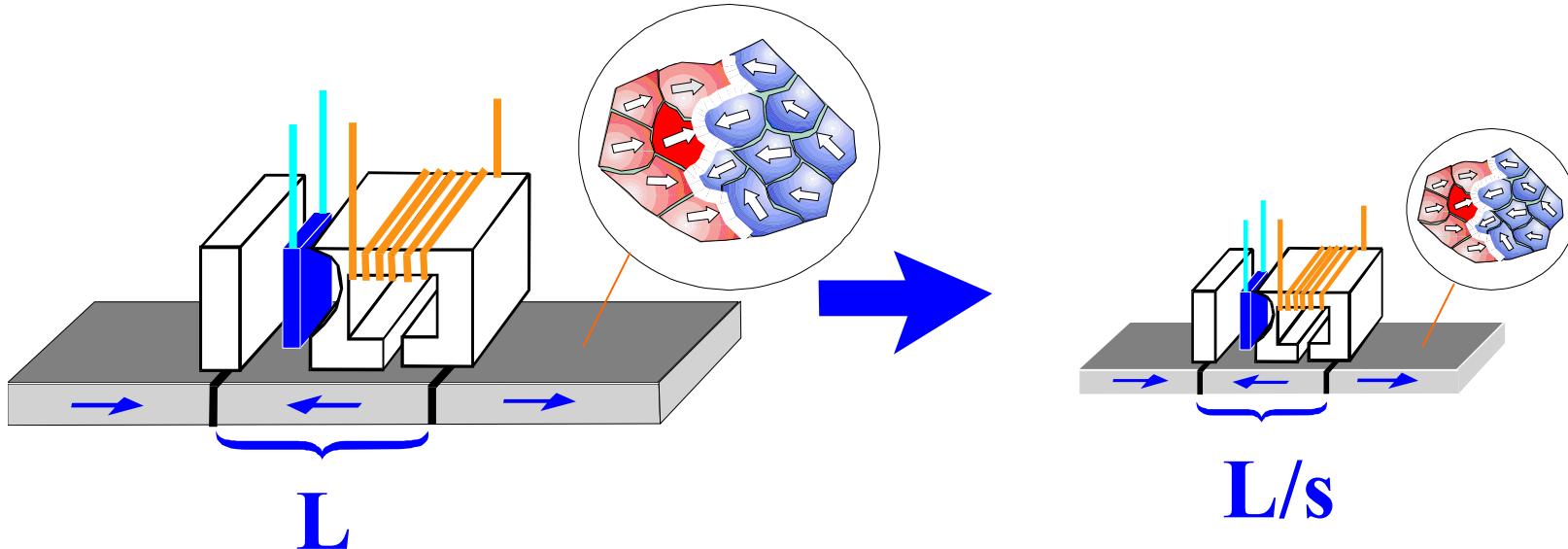
MFM

Eames, et al.
U. of Minn.

$$\text{SNR} \propto \sqrt{N} \# \text{ grains/bit}$$

More uniform the grains the better

Scaling

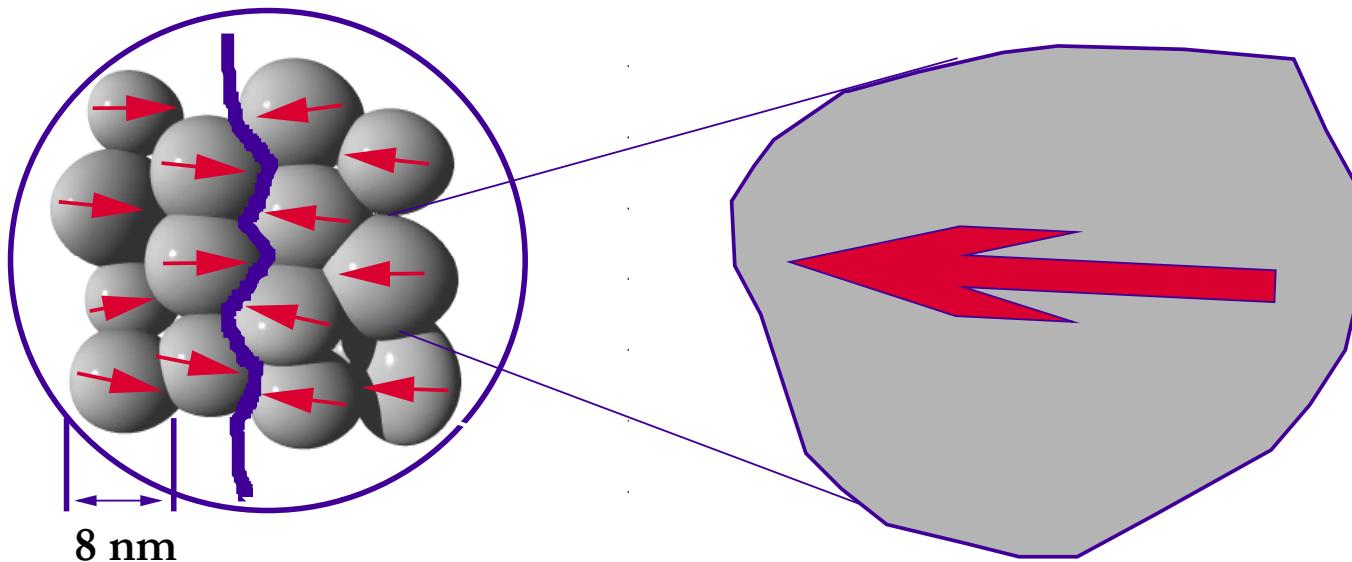


- Shrink everything by factor s (including currents and microstructure)
- Areal density of data increases s^2

But:

- Requires vastly improved processes
- Signal-to-noise drops (→ improve media, head, electronics)
- volumes scale by $1/s^3$ and surface/volume scales as s
- current densities increases by s ($\times 10^7$ A/cm 2)
- Physics no longer scales

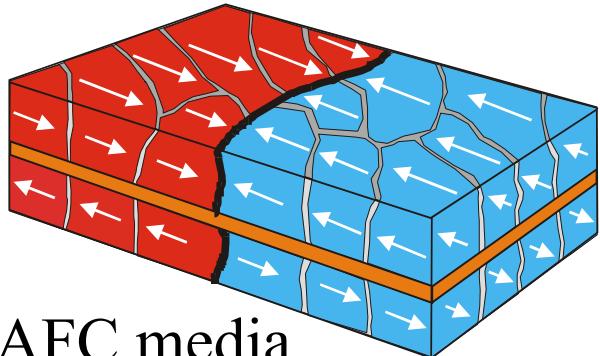
Superparamagnetic limit



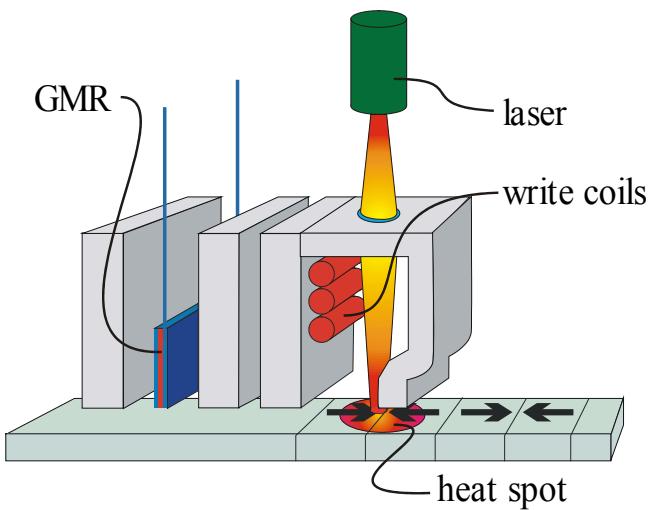
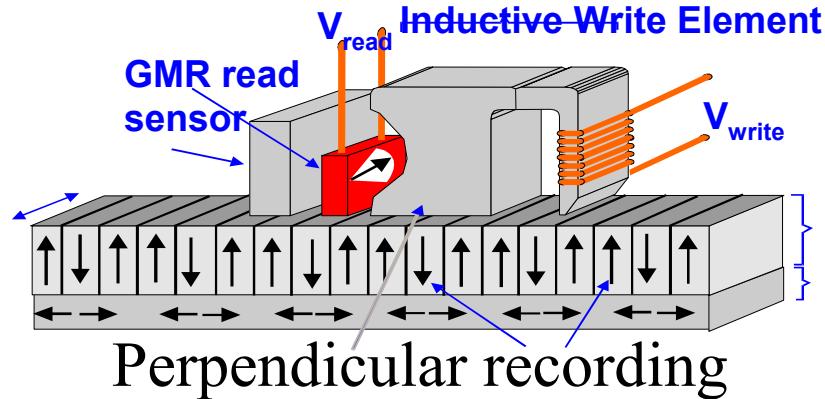
Particle energy $E = K_U V > 55 k_B T$

Particle coercivity $H_C = K_U/M < H_{head}$

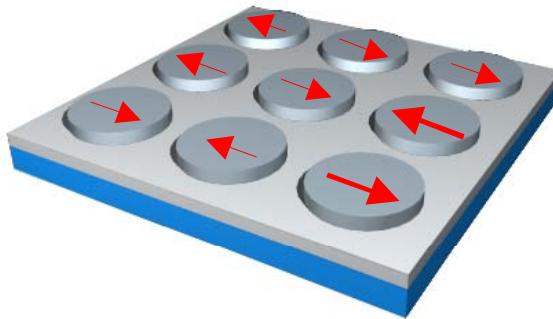
Advanced media and systems



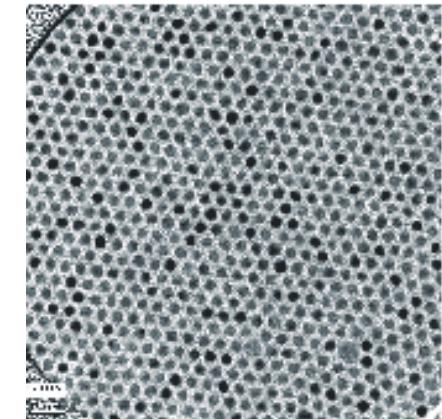
AFC media



Thermal assisted recording



patterned media



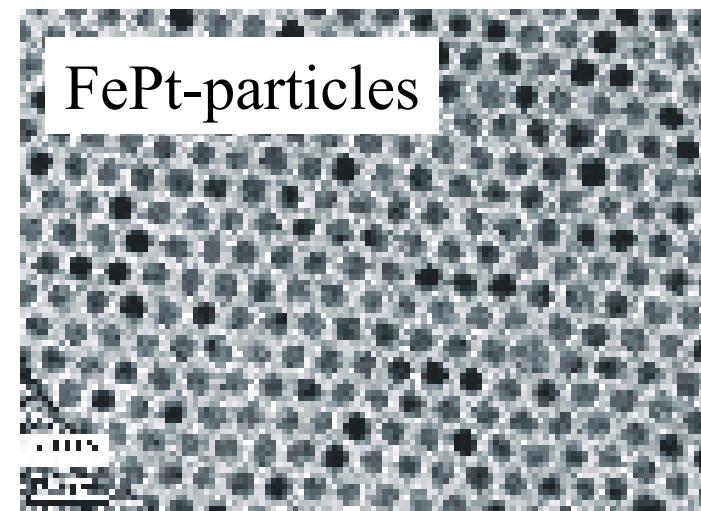
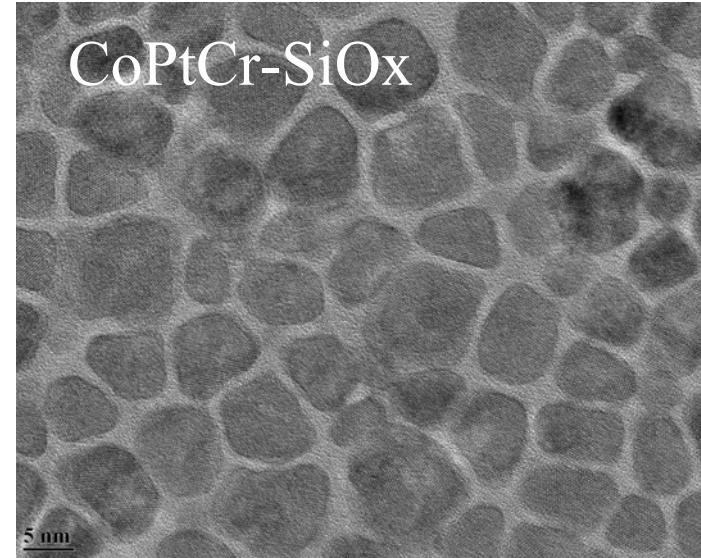
S. Sun, IBM
self-organized media

Moser et al., J. Phys. D: Appl. Phys. **35**, R157 (2002).

Terris and Thomson, J. Phys. D: Appl. Phys. **38**, 199 (2005).

Nano ‘issues’

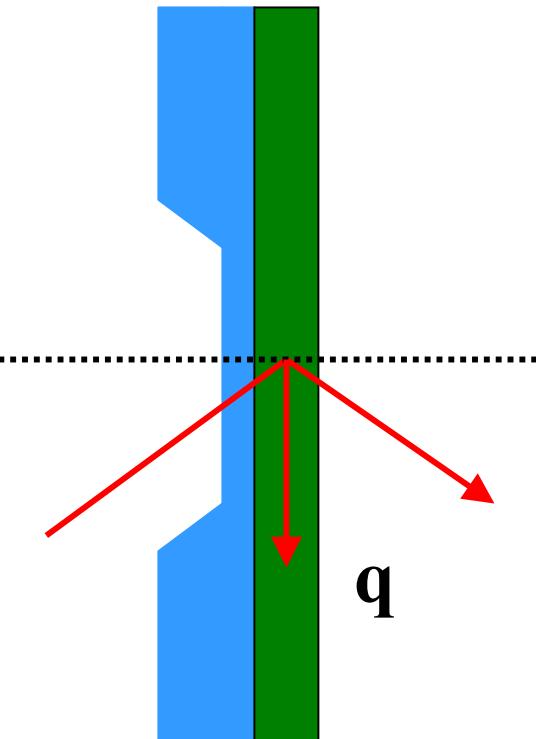
- control of nano-structural order
 - chemical segregation
 - layered heterostructures
 - lithography
 - self-assembly
- link structure/magnetic
 - Short-range exchange
 - Long-range dipolar
- thermal energy
 - spin wave modes of small structures
 - collective modes
- high current densities
 - dipole fields, spin torques, heating
- sub-ns reversal
- particle-to-particle variations
- particle-to-particle interactions



Soft x-ray techniques

- Want to link structure and magnetism
 - atomic depth resolution
 - <10 nm lateral resolution
 - <ns temporal resolution
 - intra- and inter-layer correlations
- Soft x-rays
 - 3d-TM L-edges $2p \rightarrow 3d$ transitions (550-900)
 - RE M-edges $3d \rightarrow 4f$ transitions (800-1600 eV)
 - $\lambda = 1 - 2 \text{ nm}$
 - tuning **energy** gives **element** specificity
 - tuning **polarization** gives **magnetic** specificity

Small-angle scattering



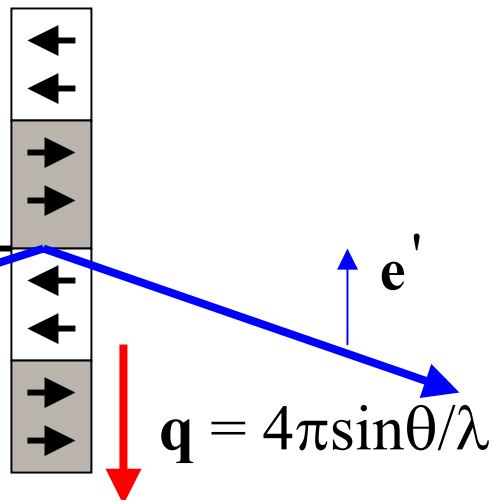
scattering arises from in-plane
inhomogeneities (2-300 nm)

- Microstructure
- Grains
- Chemical segregation
- lithography
- Magnetic disorder (*e.g.* domains)

Kortright et al., Phys. Rev. B **64**, 092401 (2001)

Magnetic domain scattering

charge	magnetic -XMCD	magnetic -XMLD
$f_n = (e^* \cdot e) F_n^{(0)} - i(e^* \times e) \cdot M_n F_n^{(1)} + (e^* \cdot M_n)(e \cdot M_n) F_n^{(2)}$		



magnetic scattering

$$f_n \propto \mathbf{M}_n$$

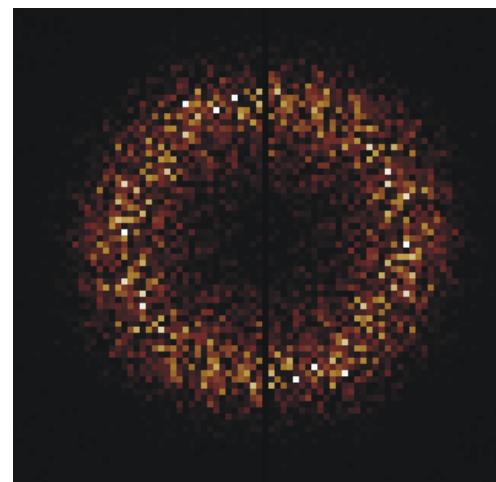
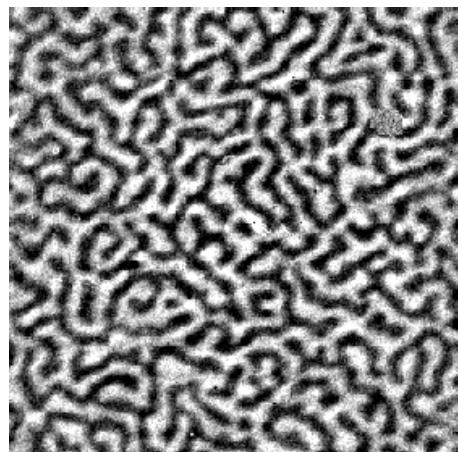
$$I = \left| \sum \exp(i\mathbf{q} \cdot \mathbf{r}) \right|^2$$

Scattering $\propto |\text{Fourier Transform}|^2$ (PSD) of the domain distribution

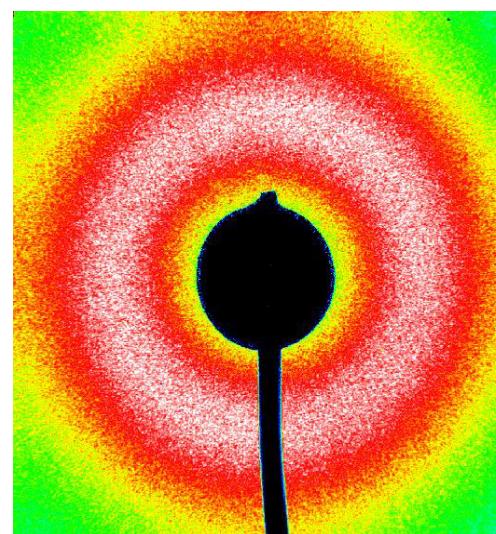
Real vs. reciprocal space

Domains in a Co/Pt ML

$5 \times 5 \mu\text{m}^2$

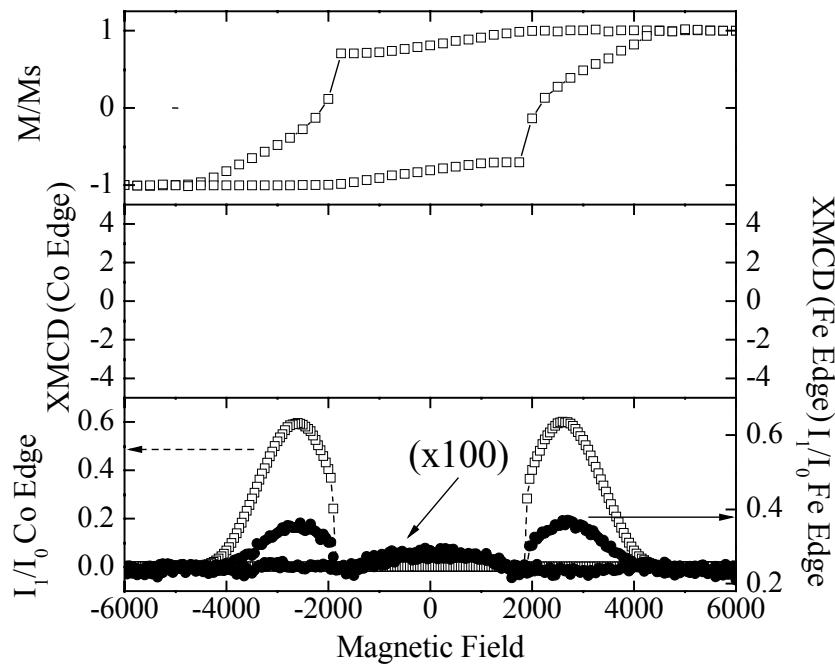
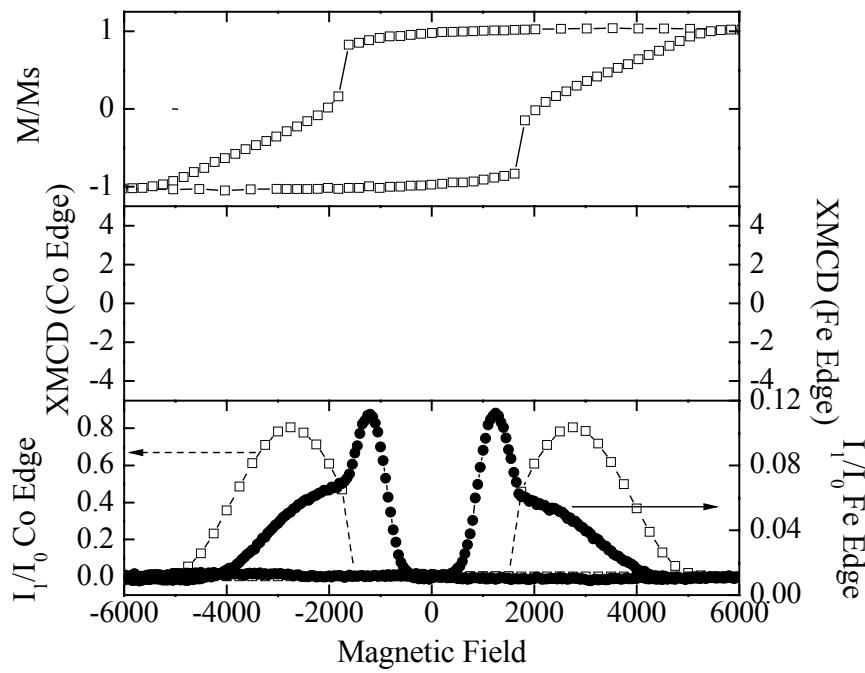
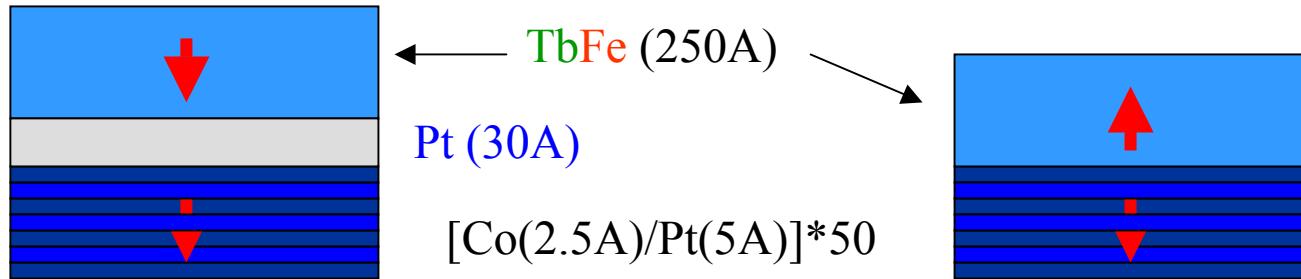


FT



X-ray
Imaging microscope

Coupled layered systems



Magnetic + charge scattering

$$I_{\cancel{\theta}} = \frac{f_c s_c}{s_m \cancel{x}^2} f_m$$

Assumptions:

- small θ
- $\mathbf{k} \parallel \mathbf{M}$

$$I_+ \propto f_c^2 s_{cc} + f_m^2 s_{mm} + 2 \operatorname{Re}[f_c^* f_m] s_{cm}$$

$$I_+ + I_- \propto f_c^2 s_{cc} + f_m^2 s_{mm}$$

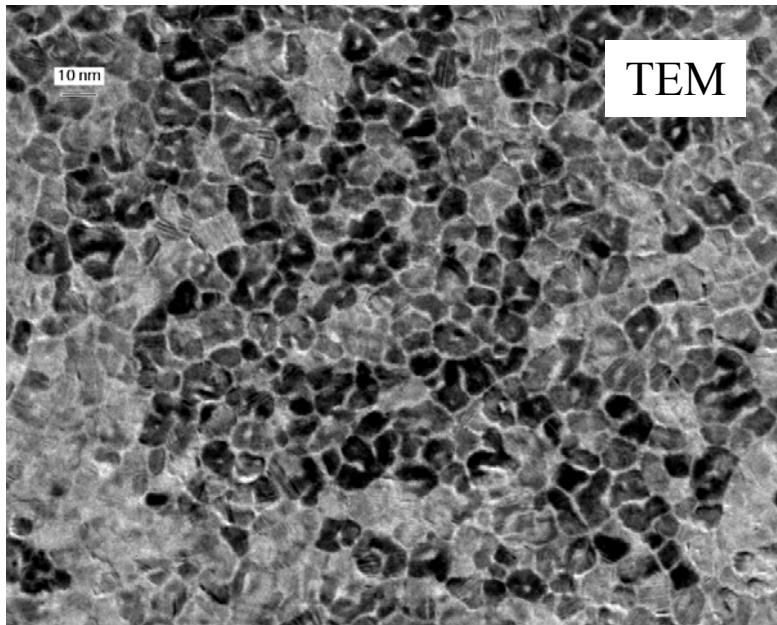
linear
pure magnetic *plus* pure charge

$$I_+ - I_- \propto \operatorname{Re}[f_c^* f_m] s_{cm}$$

magnetic-charge cross term
see also: Osgood *et al.* JAP **85**, 4619 (1999)

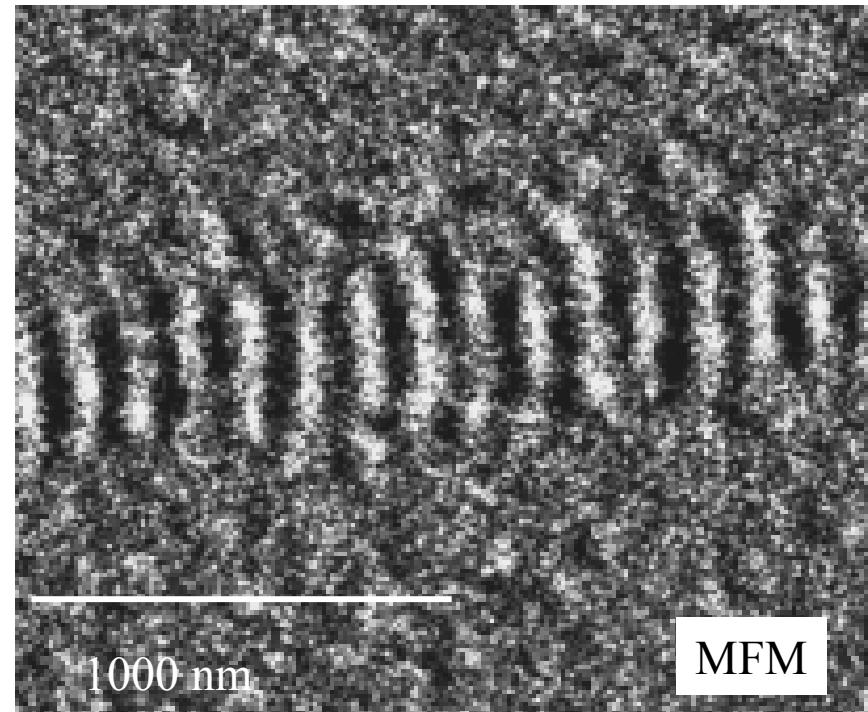
Magnetic + charge scattering

CoPtCrB alloy



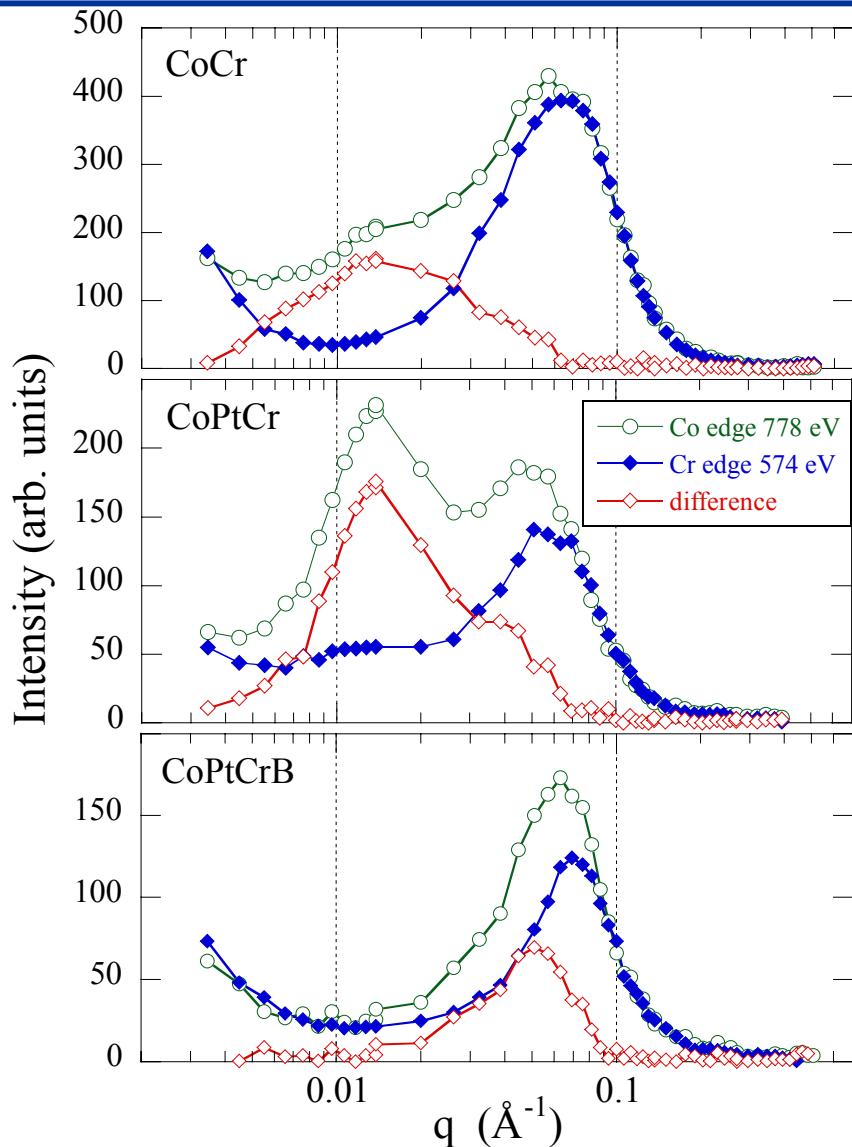
100 nm

$\langle D \rangle = 8.5 \text{ nm}$



MFM

Effect of B



Chemical / Magnetic

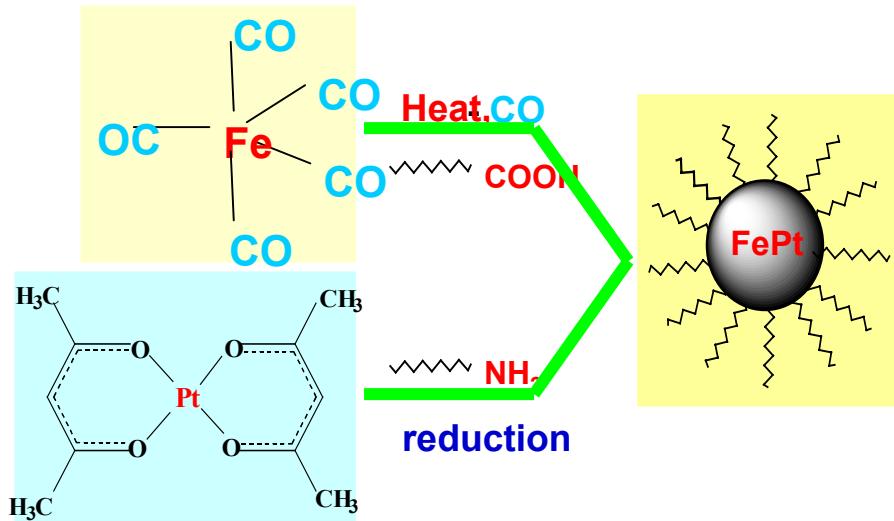
$95\text{\AA} / 420\text{\AA}$

$105\text{\AA} / 450\text{\AA}$

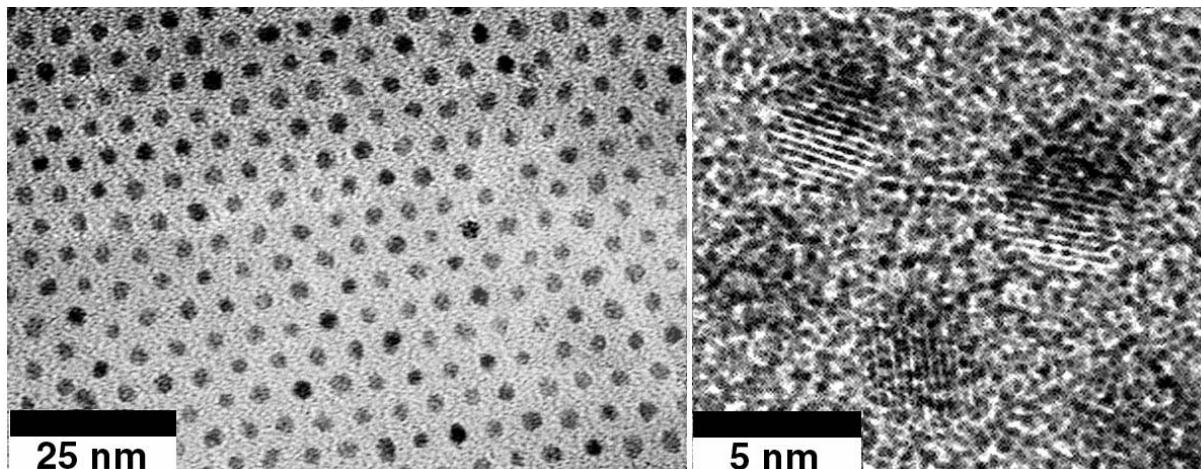
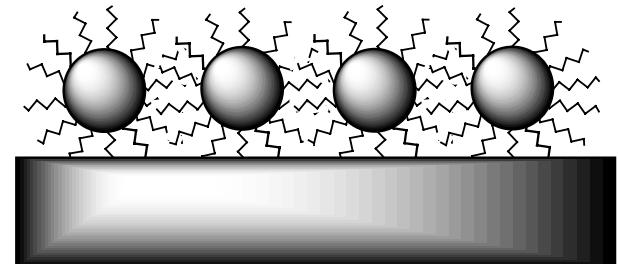
$88\text{\AA} / \sim 120\text{\AA}$

Hellwig *et al*, Appl. Phys. Lett
80, 1234 (2002).

Nanoparticle arrays



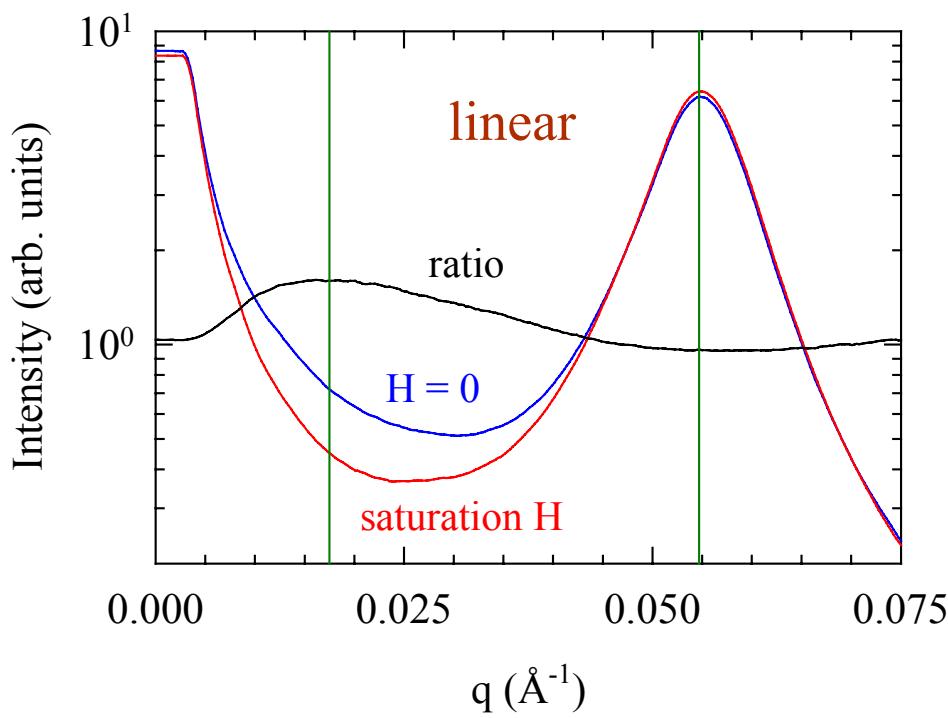
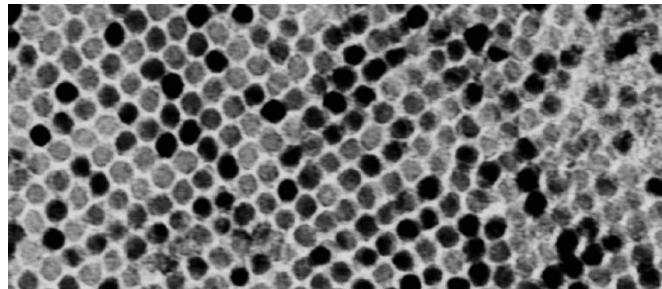
particles are coated
with Oleic acid and
oleyl amine



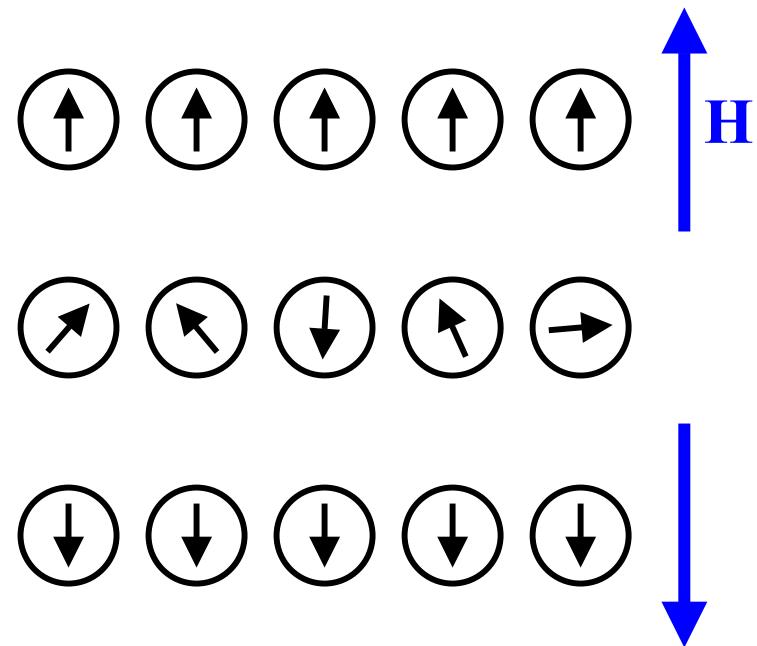
Tune: particle size
and separation

S. Sun
Brown

Magnetic scattering



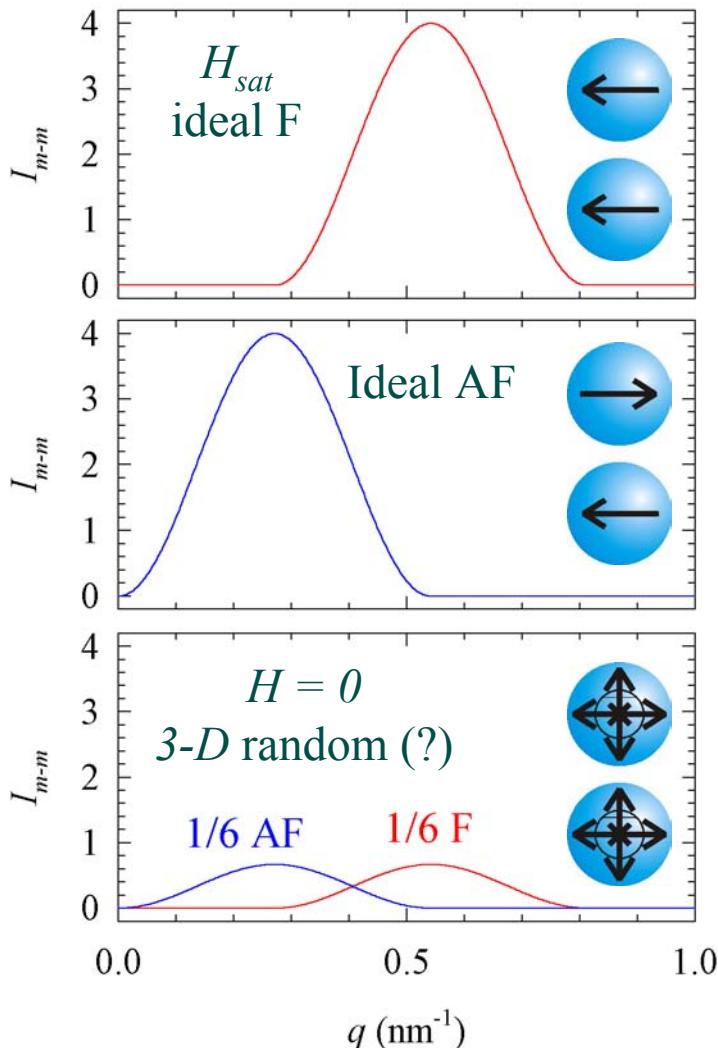
Superparamagnetic at room temperature



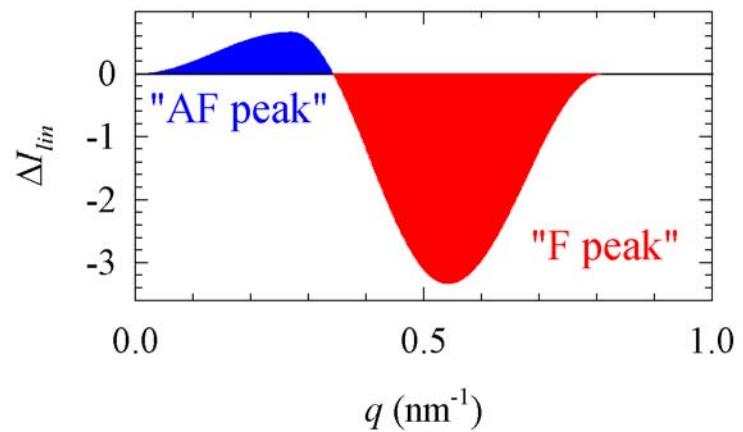
Antiferromagnetic NN and longer range closure structure

Random orientation model

Phys. Rev. B 71 012402 (2005)



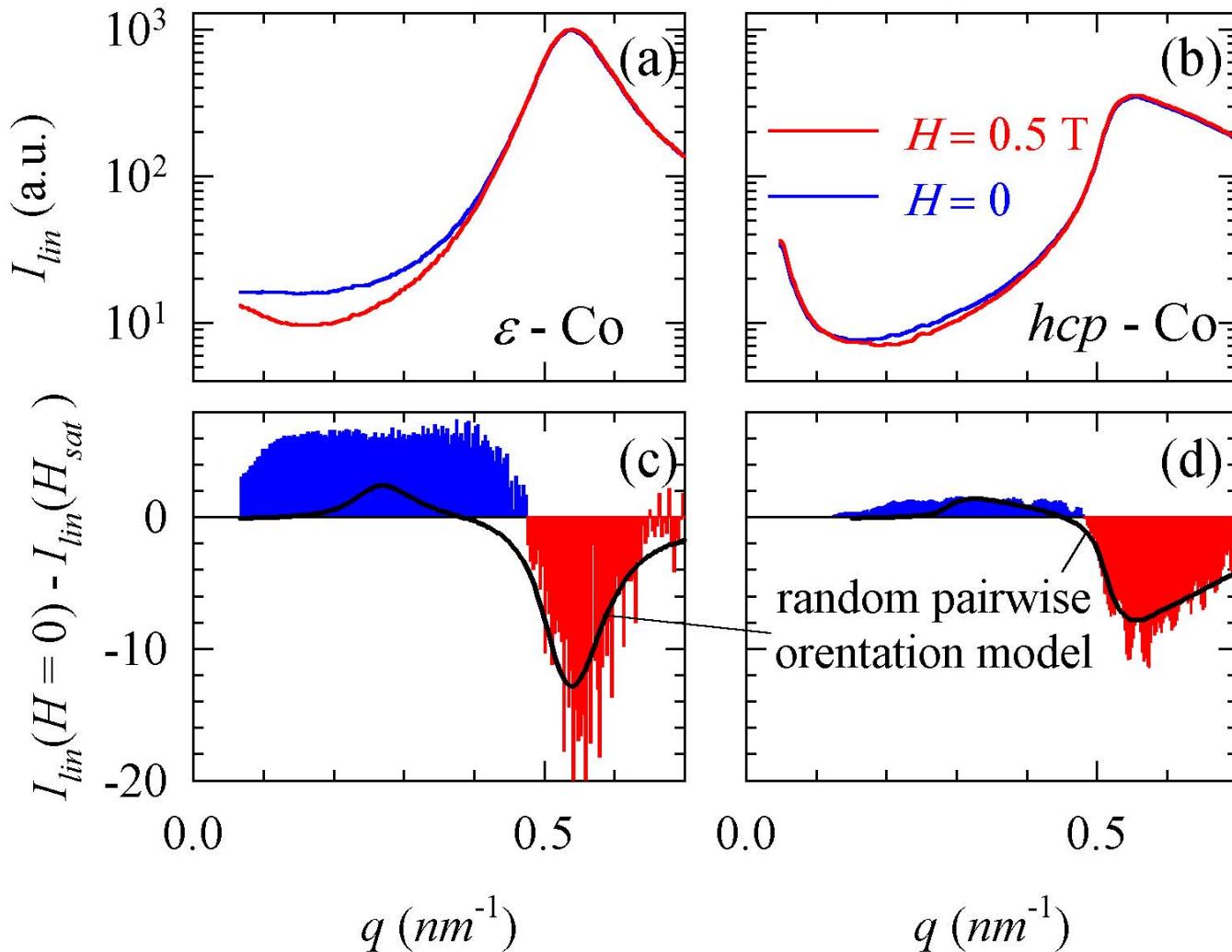
Remanent interparticle magnetic correlations are revealed in the shape of ΔI_{lin} .



For non-interacting, 3-D random particles at remanence, the AF peak area $\sim 1/5$ that of F peak in ΔI_{lin} .

Stronger than random paramagnetic scattering

Phys. Rev. B 71 012402 (2005)



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